

THE LARGE HADRON COLLIDER (LHC) IN THE LEP TUNNEL

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1. ABSTRACT

After the remarkable initial operation of LEP, the installation of a Large Hadron Collider, LHC, in the LEP tunnel will open up a new era for the High Energy Physics.

This report summarizes the main LHC parameters and subsystems and describes the more recent studies and developments.

2. INTRODUCTION

The LEP collider after a spectacular start-up in 1989 has already produced fundamental new results, including the highlight of the existence of only three particle families in the Universe. The four LEP experiments have collected to date 750 000 Z^0 events. LEP will continue to be fully exploited in the coming years, while its beam energy will be progressively increased beyond the W pairs production threshold by means of superconducting cavities.

It is appropriate then to consider a further substantive step of machine construction to enable exploration of matter at an energy level at least ten times the one of LEP. This can be done by installing in the LEP tunnel a double ring of very advanced superconducting magnets capable of handling counterrotating proton beams of app. 8 TeV, known as the Large Hadron Collider (LHC) ¹⁾.

It should be noted that this second installation will also open up the possibility of producing in LEP, in addition to electron-positron collisions, not only proton-proton collisions of 16 TeV in center-of-mass, but also electron-proton collisions up to 1.7 TeV, and eventually Pb-Pb collisions up to 1312 TeV.

CERN could then dispose of the most formidable complex of multipurpose colliders in the world.

It has recently been pointed out that the discovery of a massive Higgs particle ($m_H < 0.8 \text{ TeV}/c^2$) seems possible at the LHC, provided a luminosity L higher than $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ could be reached ²⁾. This could be obtained through the process ($H \rightarrow ZZ \rightarrow 4\mu$) using a multi-muon detector. Studies of various limiting phenomena

have shown that for an experiment without central tracking and operating alone, the ultimate luminosity could be as high as $5 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$.

This paper summarizes the expected performances and limits, the proposed lattice and the status of the various technical systems. The construction carried out in collaboration with National Institutes and European industries is compatible with the completion of LHC within a reasonable budget and time scale.

3. PROTON-PROTON PERFORMANCES

Recent experimental results with dipole models have shown that a magnetic field of $\sim 10 \text{ T}$ can be reached. Since the circumference of the LHC orbit is determined by that of the LEP tunnel, it corresponds to a top energy of app. 8 TeV per beam.

Table 1 : List of Main Parameters

Circumference	26658.833 m
Revolution time	88.924 μs
Nominal bending field	10.0 T
Nominal beam energies	7.7 TeV
Injection energy	0.45 TeV
No. of interact. regions (initially)	3
Full bunch length	0.30 m
RF frequency	400.8 MHz
Min. inter-bunch spacing	15 ns
No. of proton bunches/beam	4725
No. of protons/bunch	1.10^{11}
Intensity/beam	850 mA
Stored energy/beam	583 MJ
Total synchro. rad. (two beams)	17.5 kW
Beam radius at $\beta^* = 0.5 \text{ m}$	15 μm
Free space at I.R.	32 m
Luminosity at $\beta^* = 0.5 \text{ m}$ (for three simultaneous experiments)	$1.7 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

The other important parameter of a collider, the luminosity, is given for round beams of equal sizes by :

$$L = N^2 f k / 4\pi \sigma^2 \quad (1)$$

Here N is the number of protons per bunch, f the revolution frequency, k the number of bunches in each beam and σ is the r.m.s beam radius at the crossing points. σ is determined by the normalized beam emittance ϵ^* expressed in mm.mrad

$$\epsilon^* = \gamma \sigma^2 / \beta^* \quad (2)$$

β^* being the beta value at the crossing point and γ the energy in proton rest mass units.

3.1. Beam-beam effects

The main limitation to the collider luminosity is the beam-beam tune shift $\xi = r.N/4\pi\epsilon^*$, where r is the classical proton radius. The parameter ξ multiplied by the number of interaction regions must not exceed 0.01. Therefore when the beam-beam limit is reached, the luminosity can be increased :

- by reducing the β^* in the interaction region (I.R). The limits are set by the bunch length, the magnetic strength of the corresponding quadrupole triplets, the beam dynamic aperture and the length of the straight section, L^* , available for Physics experiments. For $\beta^* = 0.5$ m, $L^* = 32$ m.
- by increasing the number of protons per bunch. Since the ratio N/ϵ^* must stay constant to satisfy the beam-beam limit, the emittance ϵ^* and hence the beam sizes must increase accordingly. Limits are set by collective phenomena for N and by the available dynamic aperture for ϵ^* . A coherent set of parameters in the case of three interaction regions is $N = 1 \cdot 10^{11}$ p / bunch and $\epsilon^* = 3.8$ mm mrad. The CERN injector chain is capable of providing such beams with a few improvements.
- by increasing the number of bunches. This allows to increase the luminosity while keeping a small number of events per collision and without changing the beam-beam tune shift. In each interaction region, there is a part with a common vacuum chamber for the two beams where several bunches of the two counter-rotating beams "see" each other. This long range beam-beam effect³⁾ increases when the interbunch spacing decreases. Limits are also given by the data handling capabilities of the Physics experiments. Since the SPS operates with an RF frequency of 200 MHz, the interbunch spacing in the LHC must be a multiple of 5 ns. The minimum interbunch spacing could be 15 ns, while operation at 30 ns or 45 ns could be provided with minor additions to the R.F. accelerating system of the PS injector.

In order to keep the long range beam-beam effect within tolerable limits, the beam crossing angle, α has to be increased at high luminosity. This in turn reduces the luminosity according to:

$$L(\alpha) = L(\alpha = 0) / \{1 + (\alpha \sigma_L / 2 \sigma_T)^2\}^{0.5} \quad (3)$$

where σ_L, σ_T are respectively the r.m.s longitudinal and transverse beam sizes.

3.2. Synchrotron radiation

Protons of app. 8 TeV in the LHC emit synchrotron radiation with a critical photon energy of 69 eV. Each beam with an intensity of $4.8 \cdot 10^{14}$ p radiates 9 kW. The synchrotron radiation is absorbed by a radiation shield cooled at 4.2 K. Remembering that to extract 1 W at 4.2 K, about 300 W are needed at room temperature, the synchrotron radiation power, P_{sync} , appears as an important limiting factor in the cost of high luminosity colliders. It is interesting to note that P_{sync} of the LHC at very high luminosity is the same as the one of the SSC at $10^{33} \text{ cm}^{-2}\text{s}^{-1}$.

3.3. Beam loss

An other limiting factor for high luminosity colliders are beam losses. If protons hit the vacuum chamber of a superconducting magnet, radiated energy is deposited in the coils and can induce a quench. Several processes contribute to systematic losses. While the 2.5 kW of inelastic secondary particles produced in each collision region is more a problem for the detector than for the machine itself, the remaining 2.5 kW of elastic particles per beam produced with small scattering angles in the three collision regions participate in a blow-up of the beam emittance and hence potentially to beam losses⁴). Other effects like long range beam-beam effects, non-linearities in the magnetic field, ripple on power supplies also contribute to beam losses. In any accelerator, there are always a few limiting apertures, where some magnets could receive much more radiation than others. Simulations have shown that at 8 TeV a continuous loss of $\sim 10^7$ p / s can quench a dipole. Therefore a beam cleaning region without superconducting magnets should be designed with a catching efficiency better than 99 %.

4. ELECTRON-PROTON PERFORMANCES

An attractive option is the possibility to collide the 8 TeV LHC beam with the LEP electron beam. In the most promising configuration, the electron beam is deviated upwards and collides head-on with the proton beam located about 1 m above the LEP median plane.

Adequate $R\vec{f}$ power is available from the LEP RF system to compensate the synchrotron radiation losses for an average circulating current of 8.4 mA at 100 GeV. It is assumed that the current scales like E^{-4} at lower electron energies and that it is

distributed over a number of bunches such that the proton beam-beam limit is not exceeded. This is possible up to a maximum of 540 bunches where the bunch spacing becomes 49.5 m. This is the smallest bunch spacing which is simultaneously a multiple of the LEP and SPS RF wavelengths.

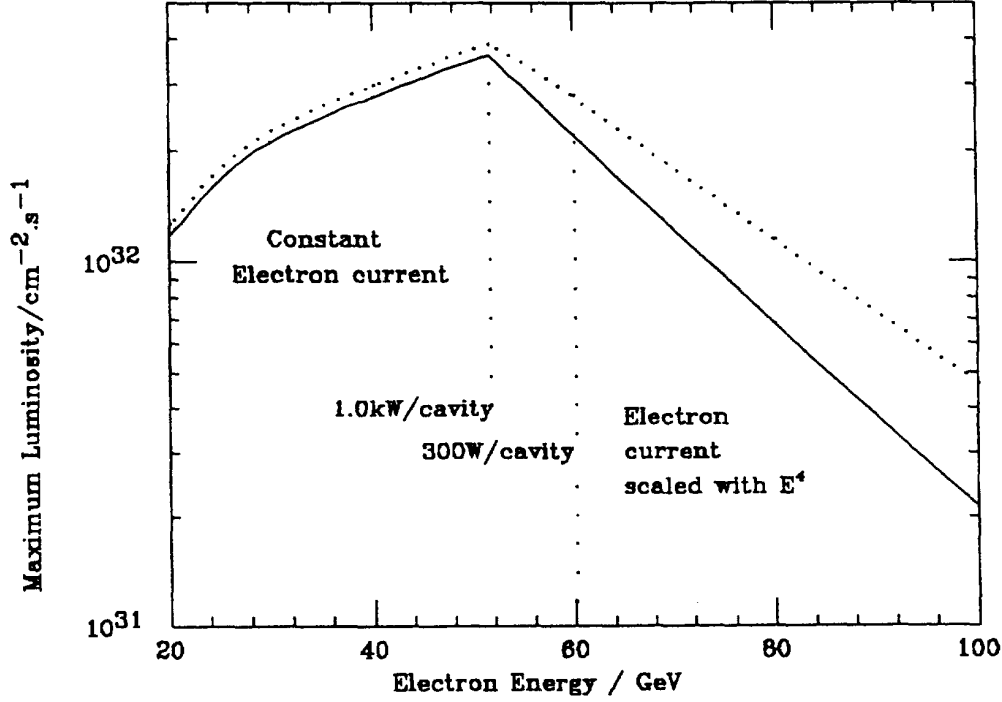


Fig. 1 : Luminosity for ep collisions (p beam energy app. 8 TeV)

The vertical betatron function at the interaction point for electrons β_{ye} is adjusted to the lowest possible value compatible with the required opening angle of the forward detector namely $\beta_{ye} = 0.15$ m. Since the number of bunches in the LHC is much smaller than in the pp mode, the proton injectors are capable of delivering intensities up to $3 \cdot 10^{11}$ protons per bunch while keeping the same transverse emittance of $3.8 \pi \cdot 10^{-6}$ rad.m. Other parameters of the electron and proton beams are adjusted so that the beam-beam tune shifts for the protons do not exceed $\xi_p = 0.006$ with one interaction region, and that the beam-beam tune shifts for the electrons do not exceed the LEP design value scaled to three interaction regions, which yields $\xi_e = 0.05$. With the assumptions and the optimization procedures described above, the luminosity obtained in ep collisions strongly depends on the energy of the electron beam, as can be seen in Fig. 1.

5. ION-ION PERFORMANCES

Any beam of fully stripped ions which can be produced by the low energy injectors (Linac, Booster, CPS) can be accelerated in the SPS and in the LHC.

With the oxygen and sulphur ion beams which have already been accelerated in the SPS one could produce a luminosity of respectively $2 \cdot 10^{26} \text{ cm}^{-2} \text{ s}^{-1}$ and $3 \cdot 10^{25} \text{ cm}^{-2} \text{ s}^{-1}$. Using the lead ion source which is now under consideration for use in the SPS fixed target programme, one would obtain a luminosity of $10^{25} \text{ cm}^{-2} \text{ s}^{-1}$.

Fundamental limitations in the LHC arise at beam crossings from electromagnetic dissociation and pair production followed by electron capture, as well as intra-beam scattering.

All these effects would limit the luminosity to around $10^{28} \text{ cm}^{-2} \text{ s}^{-1}$ for lead-lead collisions. However, to reach this luminosity, beam currents 30 times higher than those produced by the lead source presently envisaged would be necessary. This could be obtained by an improvement of the source or through an accumulation system at low energy, or by a combination of both, as discussed in Reference⁵).

For a luminosity of $10^{27} \text{ cm}^{-2} \text{ s}^{-1}$, an increase of the lead beam currents by only a factor 10 would be sufficient. Table 2 gives a list of parameters describing this case.

Table 2 : Typical LHC performance as an ion-ion collider

Type of ions	Pb
Max. c.m. energy (\sqrt{s}) for Pb-Pb	1262 TeV
Luminosity	$1.8 \times 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$
Number of I.R.	1
β^* at interaction point	0.5 m
Free space at I.R.	32 m
Number of bunches	800
Inter-bunch distance	105 ns
No. of ions/bunch	6.2×10^7
No. of ions/beam	5.0×10^{10}
Transverse emittance $\gamma\sigma^2/\beta$	1.0 μm
Transverse emittance growth times	
• at injection	10 hours
• at max. energy	15 hours
Luminosity half-life	11 hours

5.1. Lattice

Due to the size of the LEP tunnel cross section, installing two separate cryostats, one for each p beam, is not possible. The only way is to combine the two beams into the same magnet and the same cryostat. The superconducting coils providing equal but opposite magnetic fields have a common iron yoke and force-retaining structure (Fig 3), the whole being housed in one cryostat. This "two-in-one" solution allows the highest possible field in the restricted space above LEP, and has not only the advantage of compactness but also of lower cost ($\sim 30\%$), compared with that of two independent rings with separate cryostats.

LHC being in the same tunnel as LEP will also have 8 arcs and 8 long straight sections. The two proton beams, horizontally separated by 180 mm in the arcs, alternate from the outside to the inside in the middle of each of the 8 long straight sections, where in principle they could interact.

The evolution in High Energy Physics can lead some existing LEP experiments to be converted into an ep or pp experiment using LHC. In the early stage of the LHC project, it is then mandatory to maintain the maximum of flexibility among the 8 intersection regions, IR. The lattice has then been adjusted in such a way that identical performances can be reached in each IR. To reduce the beam-beam effect, the beams are vertically separated in the crossing regions when the beams are not colliding.

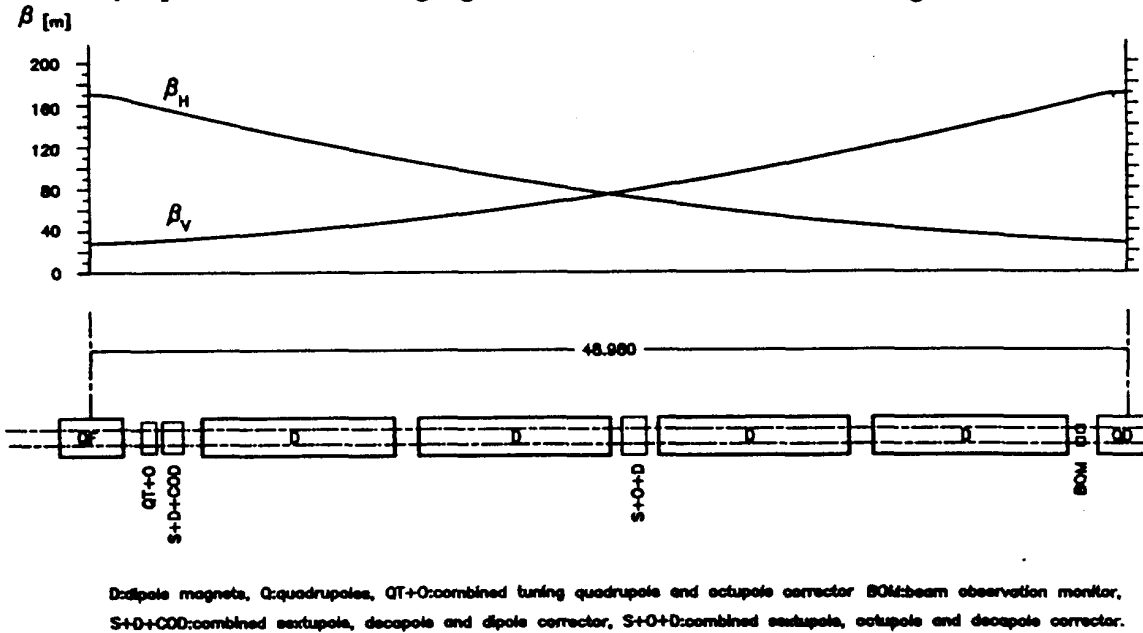


Fig. 2. Layout of the standard half-cell

The LHC lattice of FODO type is constituted by :

- 8 arcs, each of them containing 50 half cells.

One half of a regular cell (Fig 2) consists of four , ~ 9 m long, dipoles (D), a focusing (or defocusing) main quadrupole (Q). Near each main quadrupole and for each ring stand a beam observation station (BOM), a tuning quadrupole (QT), a vertical or horizontal dipole to correct the closed orbit (COD), a set of multipolar correctors sextupole (S), octupole (O), decapole (D). Lumped correctors (S+O+D) are also foreseen in the middle of the half-cell. All these magnets are superconducting.

- 8 insertions, each of them containing one long straight section and two dispersion suppressors of a type that allows trajectories of identical length for the hadrons in LHC and for the leptons in LEP. Two IRs are reserved, one for the beam dumping system, the other as a beam cleaning region.

Initially up to three IRs can be devoted to Physics experiments. The 'standard' IR can be tuned between $0.5 \text{ m} < \beta^* < 15 \text{ m}$, namely in a range between 1 (max. luminosity $1.7 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$) and 30 (min. luminosity $5.5 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$), with a length available for the detector of $\pm 16 \text{ m}$ and a bunch spacing of 15 ns.

If a specific experiment operating alone can accept a bunch spacing of 45 ns, its maximum luminosity can reach $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$.

6. MAGNETS

As far as superconducting magnets are concerned, the LHC enters now in an era of building prototypes in close collaboration with European industry. Results of single aperture NbTi and Nb₃Sn dipole models were reported in an other Conference⁶). Four NbTi and one Nb₃Sn twin aperture, 1m long dipoles are being built by four different European firms and will be delivered at CERN by end of this year. The first NbTi twin aperture, 10 m long dipole, built with HERA coils (Fig. 4) has been assembled and has been mounted into its cryostat this summer. It will be cooled at 1.8 K and tested at Saclay (F). Two NbTi twin aperture, 10 m long dipole, built with the LHC cables have been ordered by the INFN (I), eight others are being ordered by CERN. Prototypes of the main quadrupole, of tuning quadrupole, of dipole, sextupole and octupole correctors are also under development. The quantities of magnets to be produced are indicated in Table 3.

Table 3 : List of Magnets

		Magnetic Length (m)	Number of magnets
Dipoles	$B_0 = 10 \text{ T}$	9.00	2 x 1792
Quadrupoles	$G = 250 \text{ T/m}$	3.05	2 x 642
Tun. quads,	$G = 120 \text{ T/m}$	0.72	2 x 400
Sextupoles	$B'' = 4500 \text{ T/m}^2$	1.0	2 x 800
Orbit corr. dipoles	$B_0 = 1.5 \text{ T}$	1.0	2 x 552
Higher-order multipoles			2 x 1600

A more detailed review of the LHC magnets is given in Reference 7).

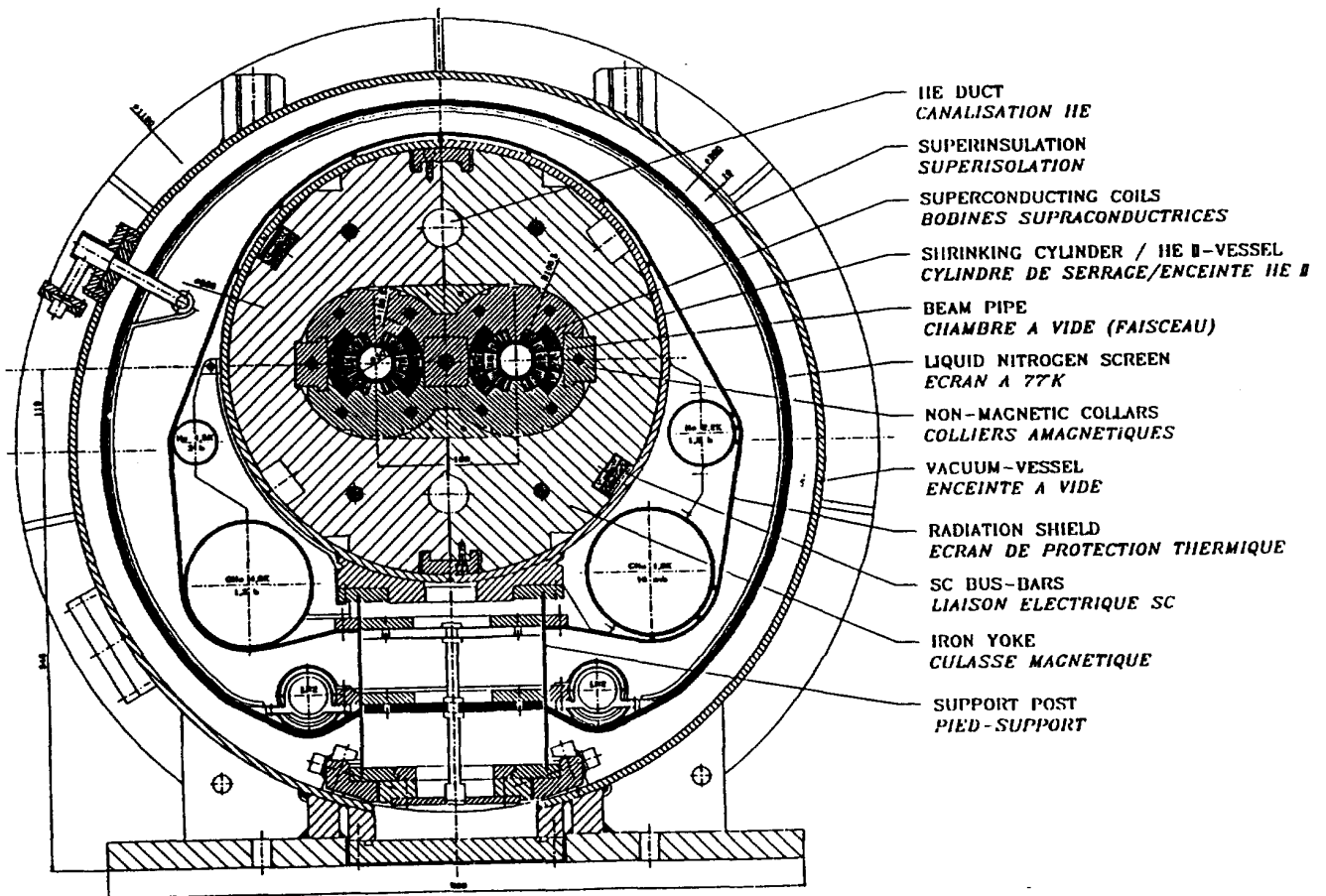


Fig. 3 : LHC dipole standard cross-section

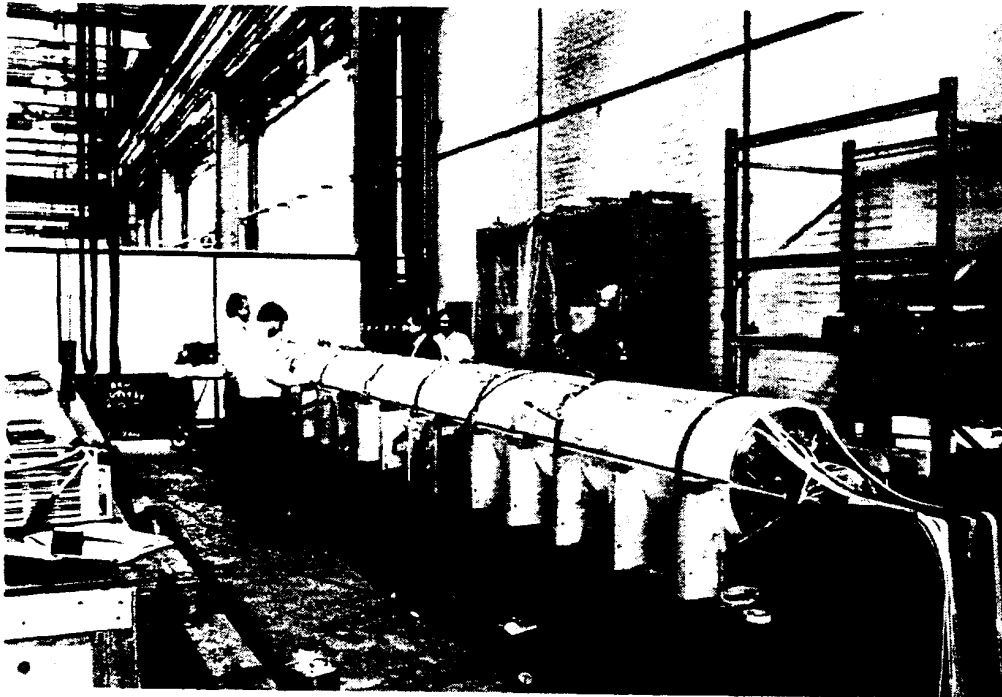


Fig. 4. 10 m long dipole

7. CRYOGENICS (FOR NBTI)

The main task of the cryogenic system is to maintain all windings at a temperature below 2 K in steady operation, as well as to cope with slow and fast thermal transients such as cooldown, current ramping and discharge, and resistive transition of the magnets.

In steady operation, the heat sources are those inherent to the cryostat design : in-leak across shields, resistive joints between cables, feedthroughs for signal or heater cables; they are estimated to 0.3 W/ metre of dipole cryostat. Another important source is due to the beam : the synchrotron radiation (critical energy < 69 eV) is fully absorbed by the inner radiation shield at about 5 K inside the vacuum chamber; an accidental beam loss can produce a quench if the heat deposit in the dipole exceeds 25 W over 50 m. It is assumed that there is only one such high heat load per half octant.

A cooling scheme based on forced circulation of superfluid helium is being considered. It appears adequate to absorb transient and localized heat loads. A pump

circulates a flow of superfluid helium in a closed loop extending over one half-octant, recooled by heat exchange in a periodic sequence of cooling stations in the machine tunnel.

8. RADIO-FREQUENCY

The basic option of the RF for LHC consist in two independent RF systems, one for each beam. The RF frequency (400.8 MHz) is twice the SPS frequency, to allow single transfer of one SPS turn. The shape of the cavities is such as to keep the 18 cm distance between the two beams. Symmetrical cavities are chosen to avoid transverse magnetic fields. An alternative is to use single-bore cavities acting on both beams and installed around an unused interaction point. Bunch to bunch feedbacks (Bandwidth > 40 MHz) are absolutely necessary in the transverse and longitudinal planes.

To cope with single bunch collective effects at high luminosity ($N=1 \cdot 10^{11}$ p / bunch), the bucket area must be large enough. A RF voltage of 18 MV corresponding to a 9.25 eV.s bucket area is considered adequate.

For a hadron collider ($\Phi_S \sim 0$), the RF power is mainly needed to handle the heavy transient beam loading created by the uneven beam structure, mainly due to beam holes required by the injection ($\sim 1 \mu s$) and dump kickers ($\sim 2 \mu s$).

Only a small fraction (850 kW) of the total installed power (8 MW) is dissipated in the cavity walls.

Each 1 MW power generator drives a multi-cell π mode coupled cavity; this is a favourable arrangement to implement RF feedback needed to handle beam loading.

The PS should be equipped with a 66.8 MHz RF system to bunch the beam at 26 GeV/c flat top with a 15 ns interbunch spacing. The 8 ns bunch length are captured and subsequently compressed to 4 ns with another 66.8 MHz system in the SPS.

With an additional RF system in the PS at 33.4 MHz, one can inject one bunch in every two 66.8 MHz buckets of the SPS, giving an interbunch spacing of 30 ns

9. CONVENTIONAL FACILITIES AND INJECTOR COMPLEX

The great advantage of building the LHC in the LEP tunnel is not only the existence of the tunnel but also of all other conventional facilities such as : access shafts, handling equipments, electrical distribution, ventilation, telecommunication and computer networks.

The cooling plants being installed in the even insertions to increase the LEP energy above 90 GeV are compatible with a future e-p operation at an electron energy of 50 GeV and represent 50 % of the cooling power needed for the LHC pp operation.

The existing accelerator complex namely the 50 MeV linac, the 1 GeV Booster, the 26 GeV Proton Synchrotron and the 450 GeV Super Proton Synchrotron, which have operated for many years with world record performance both for beam output and reliability, constitute an excellent injection complex for the LHC (Fig. 5).

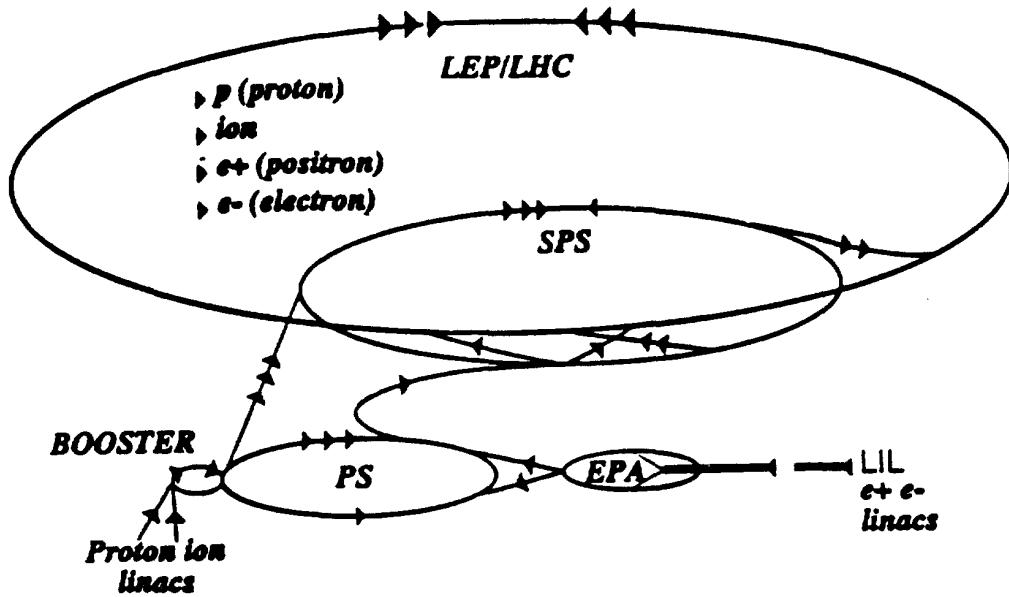


Fig. 5. Injector complex

Indeed the present beam characteristics of these injectors with minor additions would enable the LHC to reach an ultimate luminosity of $5 \cdot 10^{34} \text{ cm}^2 \text{ s}^{-1}$ for proton-proton collisions. The same existing complex, with the inclusion of, respectively, the electron/positron linacs and accumulation ring for the electrons, and of the new front-end for lead ions can provide the other particles for electron-proton and ion-ion collisions. It is appropriate to emphasize that this chain of interlinked machines represents not only a major financial asset, but also integrates decades of human efforts to push its overall performance to the present level of excellency. This is why CERN can be confident that the performance levels discussed for the LHC will be rapidly achieved.

10. EXPERIMENTAL AREAS

This design has not yet been finalized, since it depends on the experiments which are being considered.

It appears that a conceptual design of the standard LEP area, namely a cavern transverse to the beam of somewhat larger diameter, serving also as a garage, could be appropriate.

Another design being considered includes a cavern parallel to the beam, served by two large shafts at both ends for quick installation of large segments of the experiment (2500 tons each).

11. TIME-SCALE

CERN has undertaken a vigorous R&D programme for developing and actually testing on a real scale the advanced superconducting technology on which the LHC is based.

The programme is centred on the fabrication in industry of several full scale superconducting magnets by mid-1992 and finally aims to install in a hall and to fully test (magnetically and cryogenically) approximately 100 m of the complete magnet structure under realistic operating conditions.

If the final executive decision to proceed with the project is taken at that time, the installation of the LHC collider could be completed by 1997 and its commissioning could start at the beginning of 1998.

The LEP energy upgrade by means of RF superconducting cavities will be completed at the beginning of 1994, allowing LEP to be operated at or above the W-pair threshold for three years prior to the shutdown for the installation of the LHC in 1997.

In the years after 1997, when the two colliders coexist in the LEP tunnel, alternate periods of running will be scheduled on a half or full year alternate operation basis.

12. COLLABORATION WITH EUROPEAN INSTITUTES AND INDUSTRIES

The R&D programme for the development of the LHC magnets and cryogenics is based on the best use to be made of the expertise existing outside CERN in the Member States, in order to avoid carrying out in the laboratory work which could be done elsewhere. National Institutes, Universities and Industry were invited to join

forces with CERN in a complementary fashion in order to fulfil the basic aims of the programme

To date, a number of collaborations have been established and have produced very encouraging results.

Progress so far is a good example of how well Europe can proceed by joining all the available effort and expertise in a common programme and of how an advanced project in particle physics can stimulate technological development.

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